REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
20-06-2008	Monthly	May-Jun 2008

4. TITLE AND SUBTITLE
Reduced Power Laser Designation Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00178-08-1-9001

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Barry G. Sherlock

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of North Carolina at Charlotte, 9201 University City Boulevard, Charlotte, NC 28223.

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Surface Warfare Center
Dahlgren Laboratory
17320 Dahlgren Road
Dahlgren, VA 22448-5100

10. SPONSOR/MONITOR'S ACRONYM(S)
NSWC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is Unlimited.

13. SUPPLEMENTARY NOTES
None.

14. ABSTRACT
This work contributes to the Micropulse Laser Designation (MPLD) project. The objective of MPLD is to develop a 6-lb eye-safe micro-pulse laser system to locate, identify, range, mark, and designate stationary and moving targets. MPLD presents a range of new circuit design and signal processing problems, and the present work seeks to address some of these problems.

Work for month 2 has involved investigating the use of a negative impedance converter circuit to reduce the effect of the photodiode capacitance, investigating a two-transistor circuit for bootstrap buffering of the input stage, comparing the noise performance of the candidate amplifier designs, selecting the two-transistor bootstrap design as the circuit of choice, and comparing the performance of this circuit against that of a basic transconductance amplifier. Results of simulation indicate that the chosen circuit meets all design specifications.

15. SUBJECT TERMS
Laser Guided Weapons; Laser designation; laser rangefinders; infrared photodiodes; transconductance amplifiers.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			B.G. Sherlock
U	U	U	UU	13	**19b. TELEPHONE NUMBER** *(Include area code)* 540-653-5861

Monthly Progress Report on NSWC Grant N00178-08-1-9001

Title: **Reduced Power Laser Designation Systems**

PI: Barry Sherlock
University of North Carolina at Charlotte
Charlotte, NC 28023
Phone (704)687-2722 Fax: (704)687-2352
email: sherlock@uncc.edu

Date: July 20, 2008

I. INTRODUCTION

This work contributes to the Micropulse Laser Designation (MPLD) project. The objective of this project is to develop a 6-lb eye-safe micro-pulse laser system to locate, identify, range, mark, and designate stationary and moving targets.

MPLD uses laser pulses of much lower energy and higher repetition rates than in existing laser designation systems. Because of this, MPLD presents a range of new circuit design and signal processing problems, and the present work seeks to address some of these problems.

The remainder of the report is laid out as follows. Section II provides background information and a description of some of the research accomplishments achieved during the first month of this grant; much of Section II is extracted from the previous progress report, dated June 20, 2008. Section II provides the background necessary for Section III, which describes the research accomplishments achieved during the current period (June 21 through July 20, 2008).

II. BACKGROUND

II.1. The photodiode amplifier

A photodiode can be modeled as a current source in parallel with a capacitance, as illustrated in Figure 1.

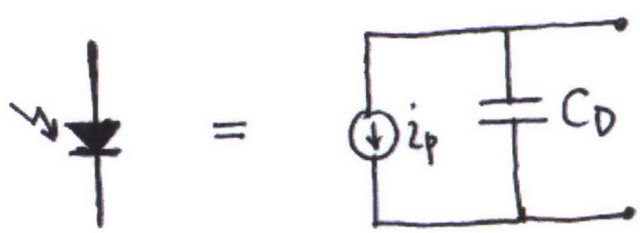


Figure 1. Photodiode equivalent circuit.

The photodiode envisaged for the present system has capacitance C_D = 225 pF. Since the signal has a bandwidth of about 3 MHz and a transimpedance gain of about 100 MV/A is desired, this presents formidable problems to the circuit designer. Because of the low power of the laser pulses, the amplitude of the input signal is very small, and therefore a further important consideration is to minimize the noise of the circuit. Unfortunately, photodiode amplifiers have very complex noise response.

The appropriate amplifier for a photodiode is a current-to-voltage amplifier (transconductance amplifier), the basic form of which is illustrated in Figure 2.

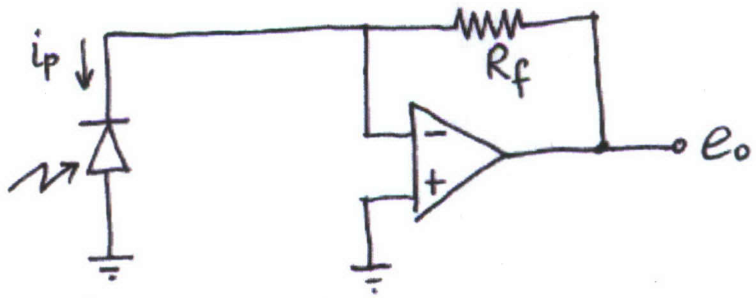


Figure 2. Basic photodiode transconductance amplifier

Because of the virtual ground at the op-amp's inverting input pin, the voltage across the diode is very small. This helps to ensure a large amplifier bandwidth by reducing currents through the diode capacitance C_D, thereby ensuring that almost all of the diode current passes through the feedback resistor R_f rather than through C_D.

Bandwidth can be further increased by decreasing the closed-loop gain of the op-amp connected to the diode. If this is done, the overall gain can be brought up to the desired value by using more than one stage of amplification, as illustrated in Figure 3. For example, setting R_f = 200KΩ, $R_1 = R_3$ = 60KΩ, and $R_2 = R_4$ = 2KΩ yields an overall transimpedance gain of 200K x 30 x 30 = 180MV/A.

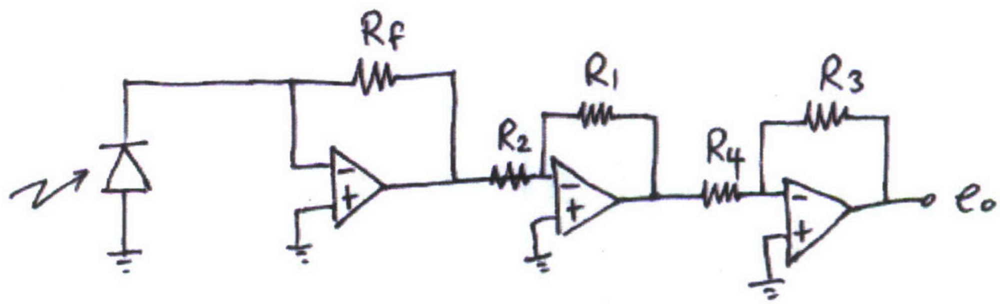


Figure 3. Three stage photodiode amplifier.

When used as a photodiode amplifier, the transconductance amplifier exhibits a complex noise behavior, in spite of the apparent simplicity of the basic circuit of Figure 2. The nature of this noise response and methods of reducing noise are presented in chapters 5 and 6 of reference [1]. The noise behavior of the photodiode amplifier has the following two undesirable properties that distinguish it from most other op-amp circuits:

1. There is "noise gain peaking" at high frequencies due to the interaction of parasitic capacitances within the amplifier. Above a certain frequency, the noise gain increases before eventually leveling off and then decreasing again once the op-amp's open-loop gain roll-off is reached, as illustrated in Figure 4 below.
2. The circuit amplifies the signal with a lower bandwidth than that with which the noise is amplified.

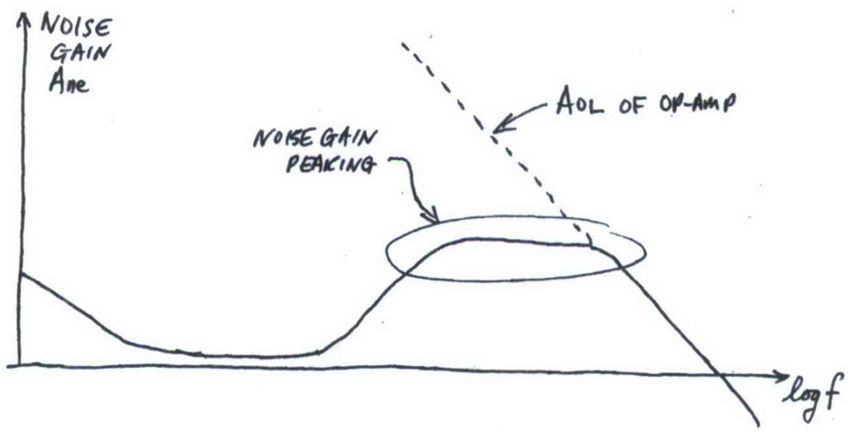


Figure 4. Photodiode amplifier noise gain, showing noise gain peaking.

This project is investigating several approaches to increasing the signal bandwidth of the amplifier, and limiting the adverse effects of noise caused by noise gain peaking and excessive noise-gain bandwidth.

II.2. Increasing bandwidth by bootstrapping the photodiode

The signal voltage across the photodiode in the basic circuit of Figure 2 is very small, of order e_0/A_{OL}, where A_{OL} is the op-amp open-loop gain. However, our application makes use of a photodiode with a high capacitance (225pF) and requires a bandwidth of about 3 MHz. This is a stringent requirement to satisfy, and it was found that even the small e_0/A_{OL} signal voltage across the diode capacitance caused the bandwidth to be too low.

Bootstrapping reduces the voltage across the photodiode even further, by connecting a unity-gain buffer across it. The idea is illustrated in Figure 5, where an ideal unity-gain buffer is connected across the diode.

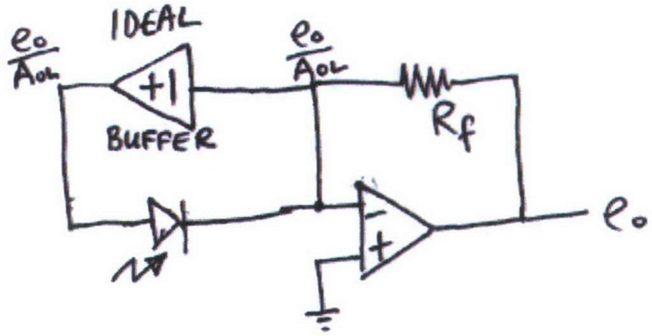


Figure 5. The bootstrapping concept.

The ideal buffer ensures that the voltage across the diode is exactly zero at all times, and of course this eliminates all influence upon the circuit by the diode capacitance C_D. This was verified by simulating the circuit of Figure 5 using a voltage-dependent voltage source for the ideal buffer.

In the real world, of course, an ideal buffer does not exist. For bootstrapping to be successful, the buffer must satisfy four stringent requirements:

1. low input capacitance (buffer input capacitance must be much less than photodiode capacitance)
2. low noise (buffer noise must be less than op-amp input noise)
3. wide bandwidth (buffer bandwidth must be much higher than op-amp bandwidth)
4. low output impedance

Figure 6 shows a modified version of the 3-stage circuit of Figure 3, where bootstrapping has been implemented using a specialized unity-gain follower, the MAX4200.

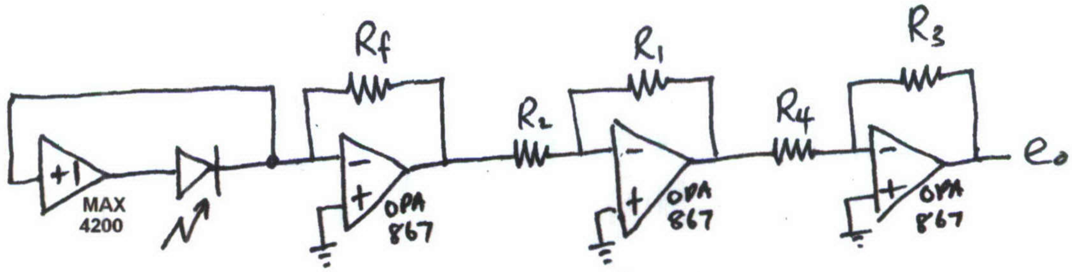


Figure 6. Bootstrapped three-stage photodiode amplifier using high-quality unity-gain buffer.

Under simulation, the circuit of Figure 6 provided greatly improved bandwidth and lower noise as compared with Figure 3. This is to be expected, because the MAX4200 has 2pF input capacitance, low noise, 660 MHz bandwidth, and 8Ω output impedance, and therefore satisfies the four very stringent requirements listed earlier.

II.3. Approaches to reducing noise

The bootstrapped three-stage amplifier circuit of figure 6 has potential for further noise reduction because the problems of noise-gain peaking and inequality between signal and noise-gain bandwidth.

<u>To reduce noise peaking</u>: One way of reducing noise is to put a capacitance across the feedback resistor R_f of the transconductance amplification stage. This functions by reducing the magnitude of the noise-gain peaking, i.e. it reduces the height of the high-frequency "bump" in the noise gain curve of Figure 4.

<u>To reduce noise-gain bandwidth</u>: A pole in the signal gain response causes it to start rolling off at a lower frequency than the noise gain response. The result is that there is a range of frequencies where the op-amp is amplifying noise and not signal. This can be dealt with by reducing the open-loop gain of the op-amp so that the roll-off in open-loop response prevents the unnecessary amplification of noise within this range of frequencies.

Figure 7 shows a variation of the basic photodiode transconductance amplifier where a second op-amp A_2 is placed <u>within the feedback loop</u> in order to modifying the open-loop response of op-amp A_1. Examination of Figure 9 shows that the modified open-loop response has the following behavior:

1. At low frequencies, C_1 is open circuit, so that the full open-loop gain of A_2 is contributed to the composite amplifier.
2. At high frequencies, C_1 is short circuit, so that A_2 contributes a gain of R_2/R_1 to the composite amplifier. (By choosing $R_2<R_1$, we ensure that this contribution is in fact an attenuation).

We see that the effect of including op-amp A_2, we are reducing the open-loop gain of the composite amplifier for high frequencies. By appropriate choice of R_1, R_2, and C_1, we can control the open-loop response such that the noise-gain bandwidth is made equal to the signal-gain bandwidth. Details are in reference [1], pages 117-118.

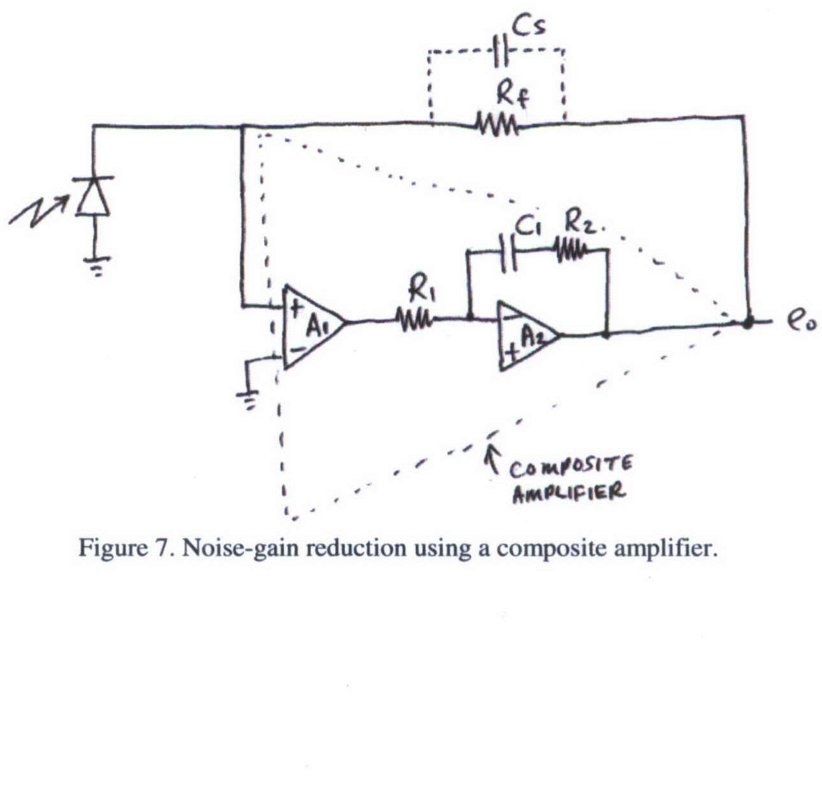


Figure 7. Noise-gain reduction using a composite amplifier.

III. RESEARCH ACCOMPLISHMENTS

The amplifier of Figure 6 has three stages and bootstrapping is achieved using a MAX 4200 precision unity-gain follower. As of the start of the current period (June 20), this was the best-performing circuit that we had yet found.

During the current period, attempts were made to design a circuit that improves upon the performance of the amplifier of Figure 6. As we shall see, these efforts were ultimately successful.

III.1. Negative Capacitance

The primary factor that limits the frequency response of the system is the very high parasitic capacitance (C_D = 225pF) of the photodiode. The basic transimpedance circuit (Figure 2) and bootstrap circuit (Figure 5) are both designed with a view to ensuring that the signal voltage across the diode is made as small as possible, thereby limiting the ability of the diode parasitic capacitance to attenuate the signal.

An alternative approach would be to design a circuit that simulates a capacitance having a negative value of C_N = -225pF. Connecting this circuit in parallel with the photodiode, one would then have $C_{total} = C_D + C_N$ = 225pF + (-225pf) = 0, thereby cancelling out the effect of the diode parasitic capacitance.

A negative capacitance can be simulated using a negative impedance converter (NIC) circuit, illustrated in Figure 8.

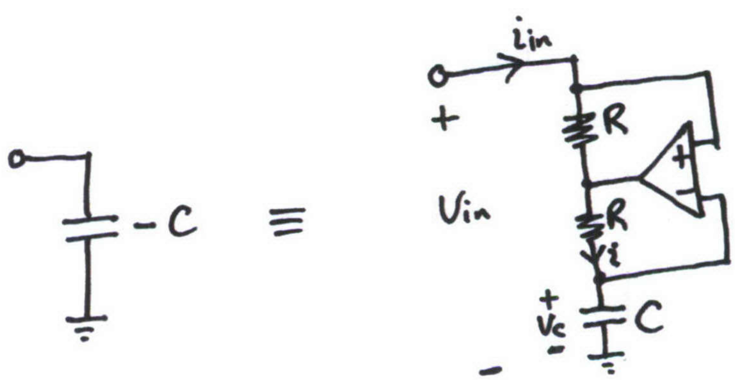


Figure 8. Using a negative impedance converter to simulate a negative capacitance.

Assuming that the op-amp is ideal, its two inputs will be at the same potential. Therefore, $i_{in}R + iR = 0$, which implies that $i = -i_{in}$. Also because of the virtual short-circuit, we have $v_C = v_{in} + 0 = v_{in}$. The capacitor obeys $v_C = i / sC$, so that the effective impedance looking into the NIC's terminal will be $Z_{in} = \dfrac{v_{in}}{i_{in}} = \dfrac{v_C}{-i} = \dfrac{1}{s(-C)}$ ohms. Therefore the circuit looks like a capacitance of –C Farads.

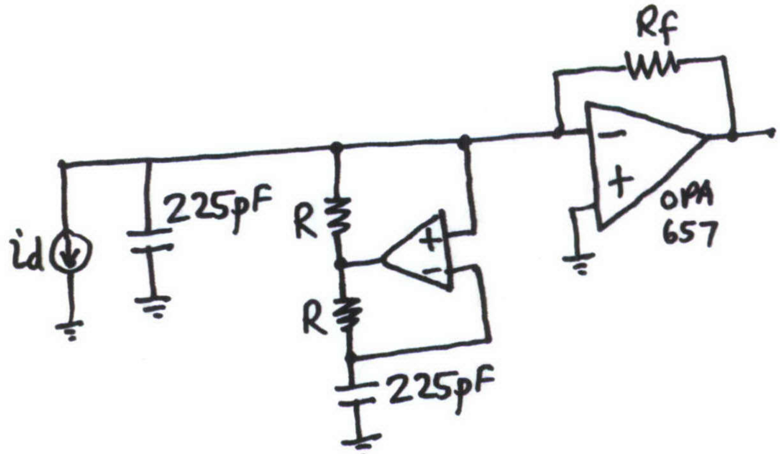


Figure 9. Basic photodiode amplifier, with diode capacitance cancelled using NIC.

Figure 9 shows the basic amplifier of Figure 2, modified to include a negative capacitance connected in parallel with the photodiode. This circuit was simulated, and was found to perform well if the NIC contained an ideal op-amp. Unfortunately, if the NIC contained any real op-amp (even one with the highest specifications available), then it was found that the simulation of negative capacitance failed at a frequency that was too low for the present application. The approach of using negative capacitance was therefore abandoned.

III.2. Two-transistor bootstrap circuit

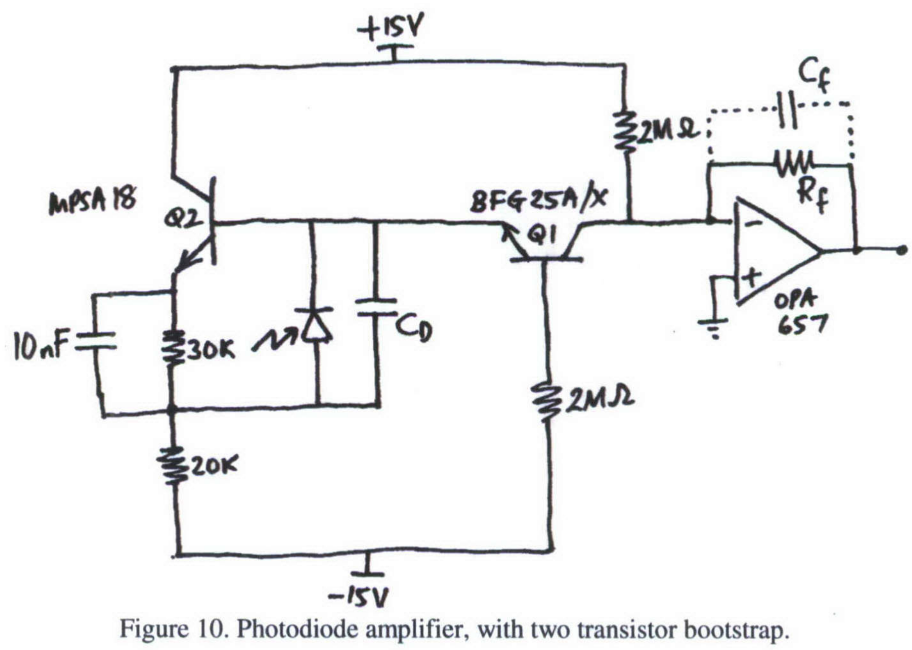


Figure 10. Photodiode amplifier, with two transistor bootstrap.

Figure 10 shows an amplifier in which the bootstrapping is achieved using a configuration of two transistors [3]. In this circuit, Q2 keeps the voltage across the diode constant, while Q1 provides current buffering.

Circuit analysis of the bootstrap portion of the circuit yields the following transfer function:

$$A_i(s) = \frac{i_{C1}}{i_D} = \frac{1}{1 + sC_D\left(1 + \frac{r_{\pi 1}}{\beta_1 R}\right)\left(R \middle\| \frac{r_{\pi 2}}{\beta_2}\right)}$$

III.3 Noise performance comparison

The following three circuits were simulated in order to compare their noise performance:

(a) The two-transistor bootstrap circuit
(b) The bootstrap circuit using the MAX 4200 unity gain buffer
(c) The bootstrap circuit using the MAX 4200 unity gain buffer and a composite amplifier.

For convenience, the circuit diagrams are repeated in Figure 11. Their noise performance up to 10 MHz is illustrated in Figure 12.

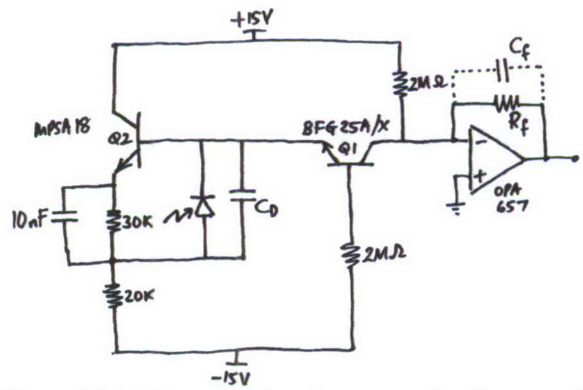


Figure 11 (a) Two-transistor bootstrap circuit

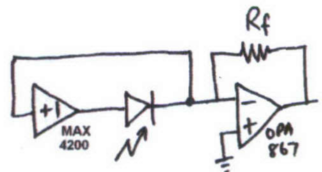


Figure 11 (b) Bootstrap circuit with MAX4200 buffer

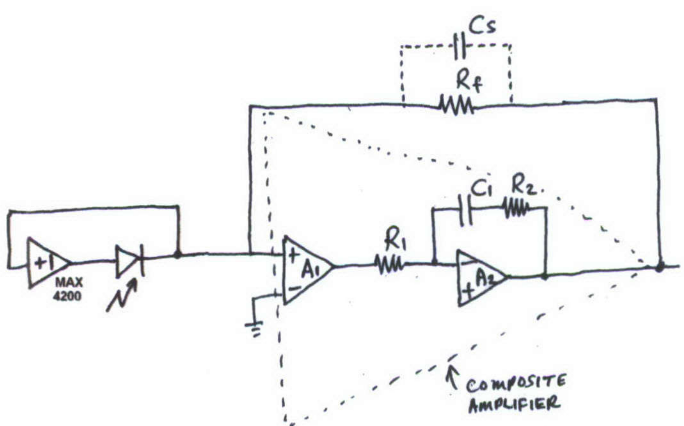
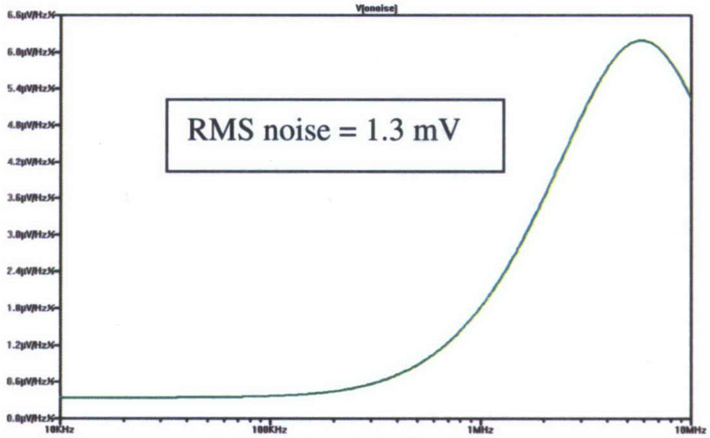
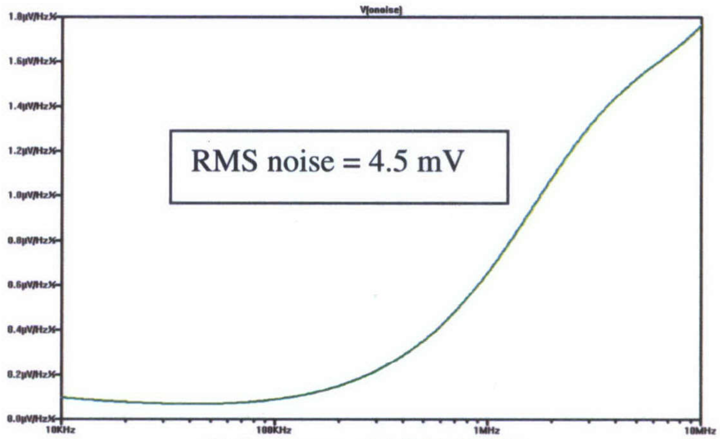


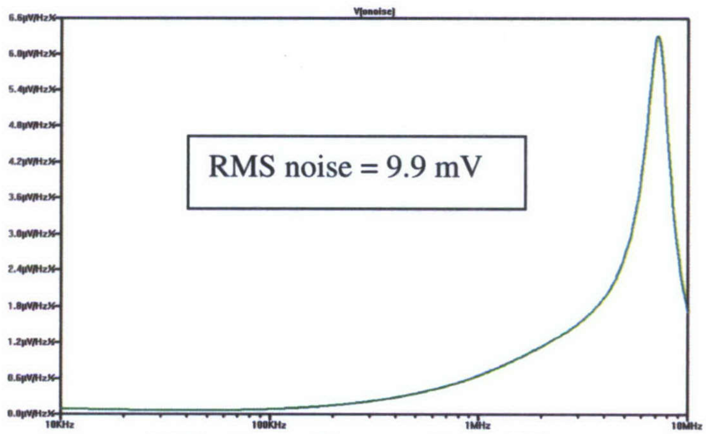
Figure 11 (c) Bootstrap with MAX4200 buffer and composite amplifier



(a) Two-transistor bootstrap



(b) Bootstrap with MAX4200



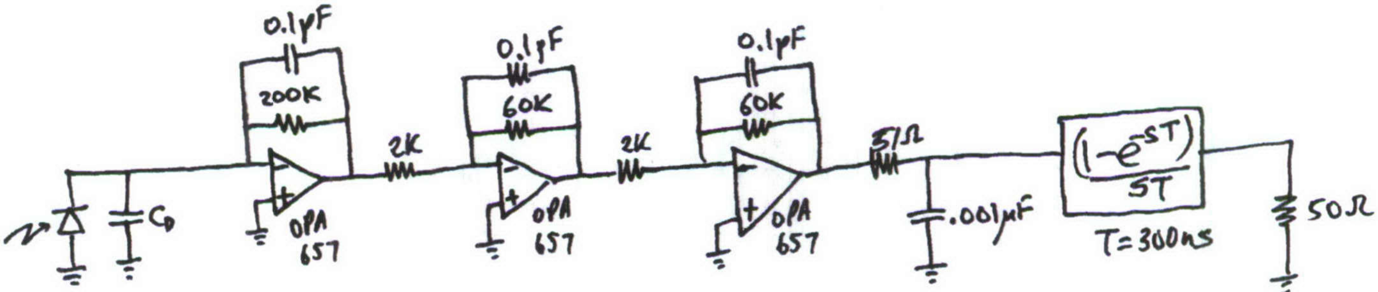
(c) Bootstrap with composite amplifier

Figure 12. Noise performance results.

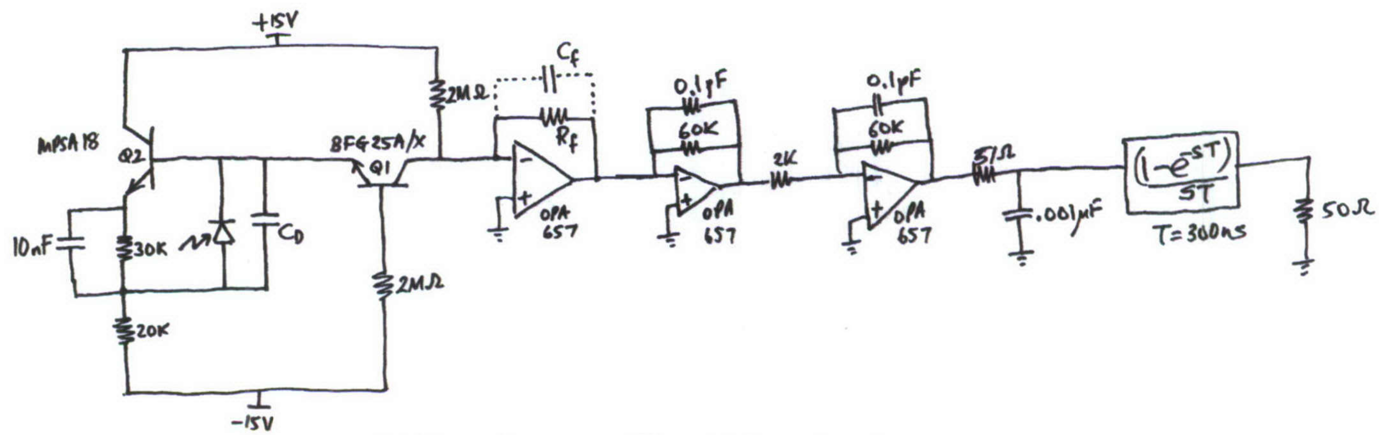
The simulations yielded overall RMS noise voltages of 1.3 mV, 4.5 mV, and 9.9 mV for circuits (a), (b), and (c) respectively. Circuit (a) exhibits clearly superior noise performance compared to the other two circuits. Therefore the two-transistor bootstrap approach was chosen.

III.4 Evaluation of chosen circuit

The two-transistor bootstrap circuit of Figure 10 was augmented with two further op-amp voltage gain stages, and was compared under simulation with the original three-stage circuit without bootstrap (Figure 3). The two circuits are illustrated in Figure 13.



(a) Original 3-stage amplifier

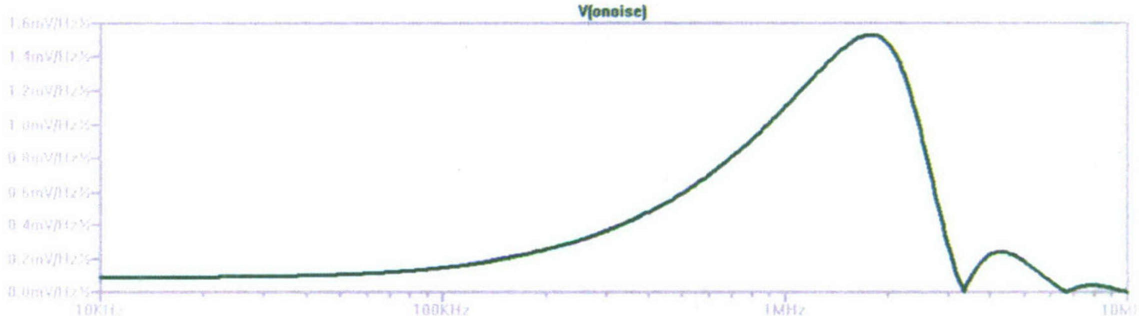


(b) Chosen 3-stage amplifier with 2-transistor bootstrap.

Figure 13. The two circuits whose performance is compared in Section III.4

The noise responses are shown in Figure 14, where it can be seen that the bootstrap circuit produces 330mV RMS noise, a considerable improvement over the 1870 mV for the original circuit.

Original: Vrms = 1.87V



Bootstrap w/buffer: Vrms = 330mv

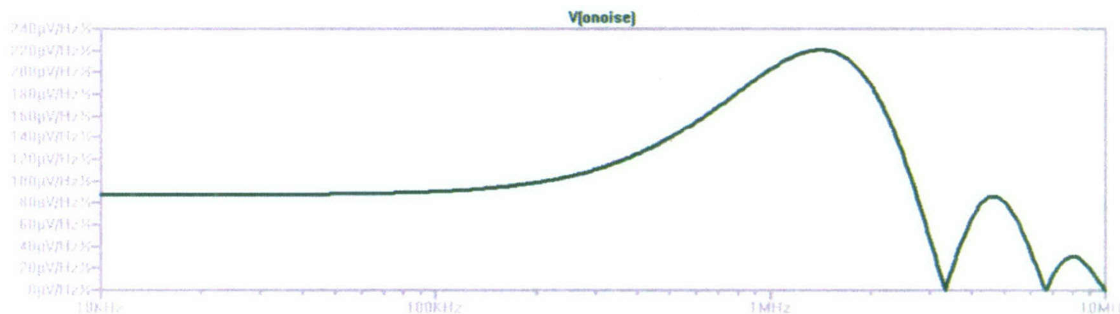


Figure 14. Noise performance of the circuits in Figure 13.

Figure 15 compares the signal gain frequency responses of the two circuits. Both circuits produce the same DC gain, but the bootstrap is very clearly superior, having a higher bandwidth (3.92 MHz versus 3 Mhz) and a flat frequency response that does not show the undesirable peaking exhibited by the original circuit.

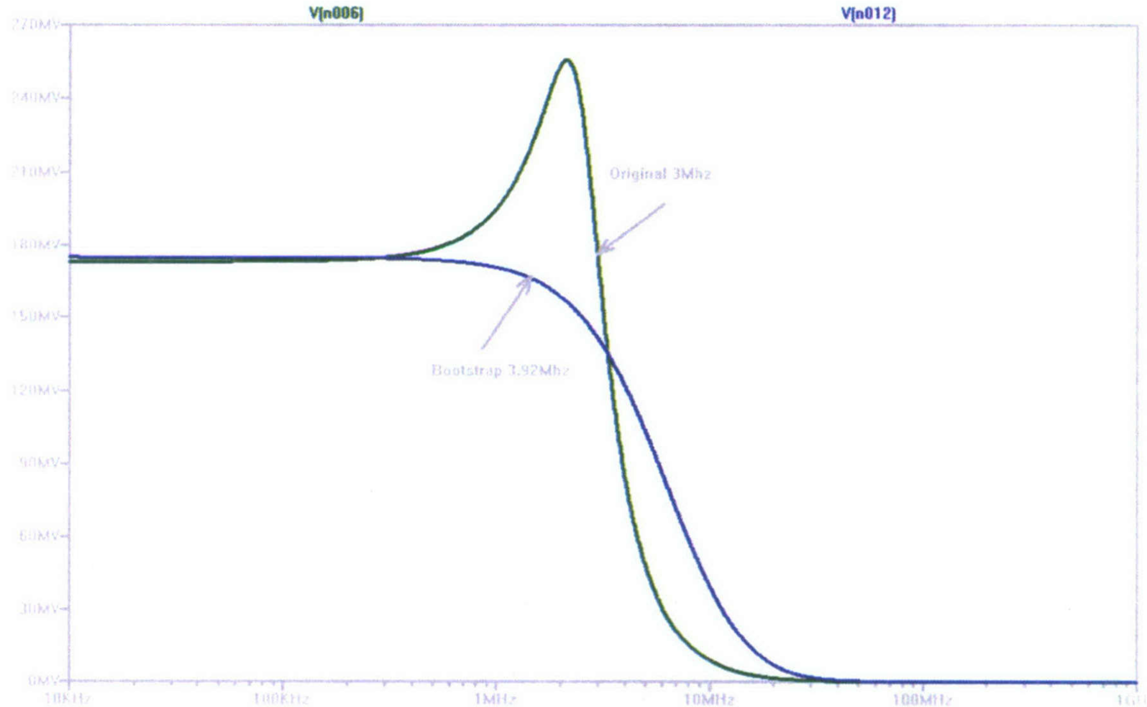


Figure 15. Signal frequency responses of the circuits of figure 13. Note the superiority of the blue curve representing the two transistor bootstrap circuit.

IV. References

1. Jerald Graeme, "Photodiode amplifiers – Op Amp Solutions", McGraw Hill 1996.
2. MAX4200 data sheet, Maxim Integrated Products, 120 San Gabriel Drive, Sunnyvale, CA 94086
3. Philip C.D. Hobbs, "Building Electro-Optical Systems", Wiley-Interscience, 2000.

Acknowledgement:

Thanks are due to Ken Nichols for the plots of Figures 12, 14, and 15.